Formal Methods for Software Development

Introduction

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Chalmers University of Technology
and
University of Gothenburg

01 September 2020

Course Team

- Wolfgang Ahrendt (WA) examiner, lecturer
- Andreas Lööw (AL) teaching assistant

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teaching assistant activities include:

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- correcting lab hand-ins
- student support via:
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  - online meetings on e-mail request

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Breakout

Information Channels

Course Home Page

On Canvas, via Chalmers and GU.
Also used for online news and discussions.

Course Structure

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Topic	# Lectures	# Exercises	Lab
Intro	1	✘	✘
Modeling & Model Checking with PROMELA & SPIN	6	3	✔
Specification & Verification with JML & KeY	6 (+1?)	3	✔

PROMELA & SPIN abstract programs, model checking, automated

JML & KeY concrete Java, deductive verification, semi-automated

. . . more on this later!

Online Course

This year, entire course held online

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Held as Zoom meetings:

- Lectures
- Exercises

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Information on Zoom access on Canvas

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Zoom

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Poll

Online Exercises

Exercises

- Held as Zoom meetings
- One exercise web page (almost) each week (6 in total)
- Discussed in next exercise session
- Play around with the exercises before coming to the session
- Have installed tools or browser interfaces readily available
- Exercise participation highly recommended

Passing Criteria

- Oral examination (via Zoom) in exam week
- Two lab hand-ins
- (No written end-exam)
- Oral exam and labs can be passed separately

Oral Exam

- Individual, oral examination

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- Slots between 26 and 30 October

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- 2 Lab hand-ins: Promela/Spin 02 Oct, JML/KeY 26 Oct
- 2 Lab Questions Sessions
- Submission via Fire, linked from course home page
- If submission is returned, roughly one week for correction

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- 2 Lab Questions Sessions
- Submission via Fire, linked from course home page
- If submission is returned, roughly one week for correction
- You work in groups of two. No exception![a]
  You pair up by either:
  1. contact people on your own
  2. post request via Canvas
  3. participate in pairing at first exercise session

  If all that is **not** successful, contact Andreas by e-mail.

[a] Only PhD students have to work alone.

Web Presence

- Canvas
- Web Pages (linked from Canvas)
- Fire System (for lab submissions)

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(inspect course schedule)

Course Evaluation

1. course evaluation group:
   - student representatives
     - randomly selected (Chalmers)
     - volunteers (GU)
   - one meeting during the course, one after
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- Sebastian Hafström (hafstrom.sebastian@gmail.com)
- Philip Nord (nordp@student.chalmers.se)
- Vallisha Somayagi (vas.atloor@gmail.com)
- Mohammad Jasim Uddin (jasim.arc@gmail.com)
- Riccardo Zanetti (znt.riccardo@gmail.com)

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- Riccardo Zanetti (znt.riccardo@gmail.com)

GU students: please consider volunteering

Course Literature

- In part I, we partly use:

  Ben-Ari Mordechai Ben-Ari
  Principles of the Spin Model Checker
  Springer, 2008
  Ben-Ari received ACM award for outstanding contributions to CS education. Recommended by G. Holzmann. Excellent student text book.
  (E-book at `link.springer.com`)

- Relevant for part II:

  KeYbook *W. Ahrendt*, B. Beckert, R. Bubel, R. Hähnle, P. Schmitt, M. Ulbrich, editors.
  Deductive Software Verification - The KeY Book
  Vol 10001 of *LNCS*, Springer, 2016
  (E-book at `link.springer.com`)

Additional Literature

Holzmann Gerard J. Holzmann
The Spin Model Checker
Addison Wesley, 2004

BayerKatoen Christel Baier, Joost-Pieter Katoen
Principles of Model Checking
MIT Press, 2008

Connection to other Courses

Prerequisites

- Skills in first-order logic and temporal logic, e.g., from
  - Logic in Computer Science, or
  - Discrete Event Systems
- Skills in object-oriented programming (like Java)

Related courses (not assumed!)

- Concurrent Programming
- Finite Automata
- Testing, Debugging, and Verification

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(anonymous)

Motivation: Software Defects cause BIG Failures

Tiny faults in technical systems can have catastrophic consequences

In particular, this goes for software systems

- Ariane 5
- Mars Climate Orbiter
- London Ambulance Dispatch System
- NEDAP Voting Computer Attack
- ...

Motivation:
Software Defects cause OMNIPRESENT Failures

Ubiquitous Computing results in Ubiquitous Failures

Software is almost everywhere:

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- Clouds
- Smart cards
- Smart devices
- Cars
- Blockchain
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software/specification quality is a growing commercial and legal issue

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- Design follows patterns that are proven to work

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- Cost efficiency favoured over reliability.
- Design practise for reliable software in immature state
  for complex (e.g., distributed) systems.

How to Ensure Software Correctness/Compliance?

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Testing against external faults

- inject faults (memory, communication) by simulation or radiation
- trace fault propagation

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- Testing is labour intensive, hence expensive

What are Formal Methods

- Rigorous methods for system design/development/analysis
- Mathematics and symbolic logic $\Rightarrow$ formal
- Increase confidence in a system
- Two aspects:
  - System requirements
  - System implementation
- Formalise both
- Use tools for
  - exhaustive search for failing scenario, or
  - mechanical proof that implementation satisfies requirements

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and

- Training in Formal Methods increases high quality development skills

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- Simple properties
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    Something bad will never happen (e.g., green light mutual exclusion)
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  - Modularity, encapsulation
  - Refinement relation

The Main Point of Formal Methods is Not

- to show correctness of entire systems
- to replace testing
- to replace good design practises

There is no silver bullet!

- No correct system without clear requirements & good design

But . . .

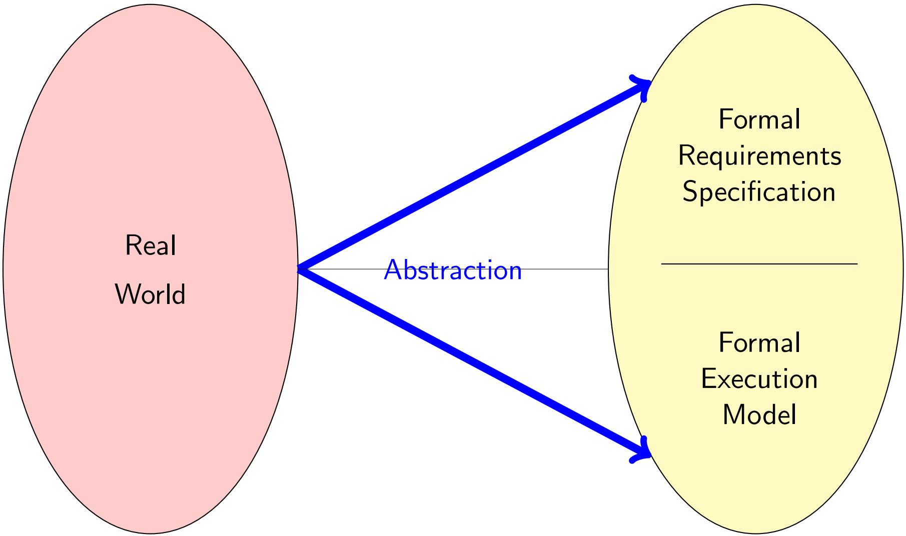
- Formal proof can replace arbitrarily many test cases
- Formal methods improve the quality of specs
  (even without formal verification)
- Formal methods guarantee specific properties of system (model)

A Fundamental Fact

Formalisation of system requirements is hard

Let's see why . . .

Difficulties in Creating Formal Models



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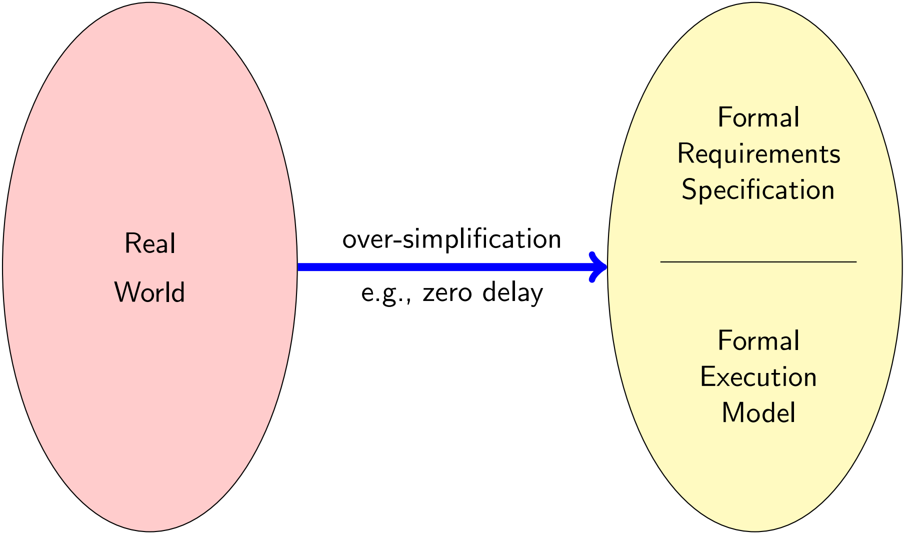

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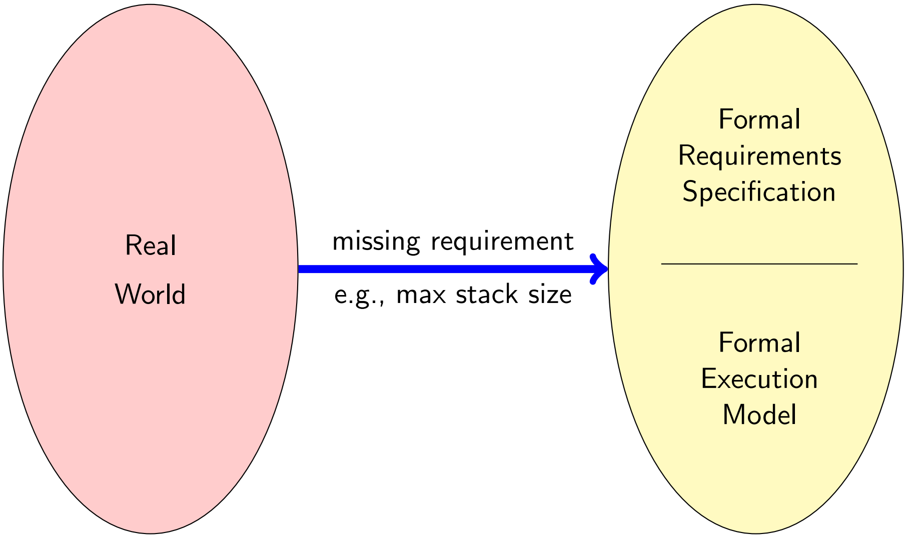

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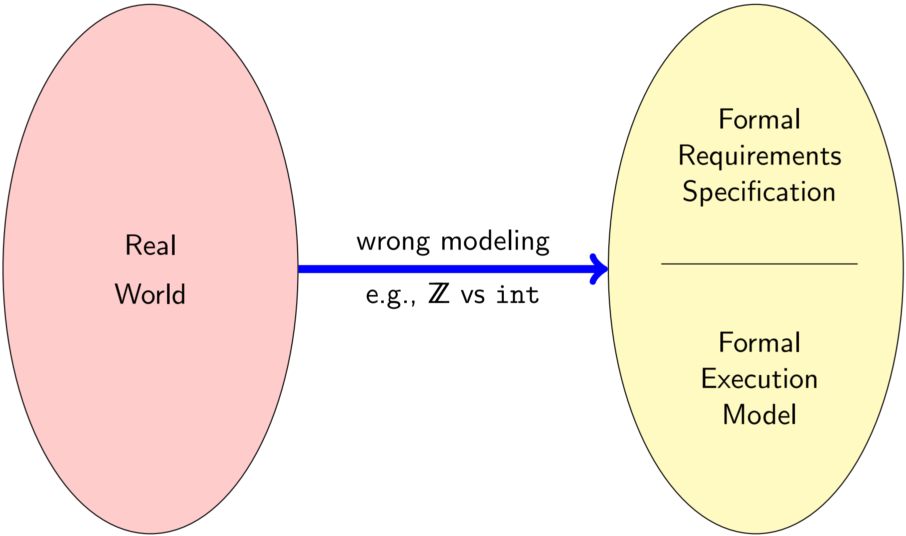

Formalization Helps to Find Bugs in Specs

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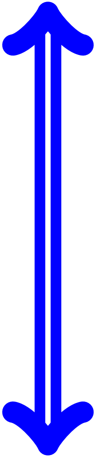
- Wellformedness and consistency of formal specs partly machine-checkable
- Declared signature (symbols) helps to spot incomplete specs
- Failed verification of implementation against spec gives feedback on erroneous formalization

Another Fundamental Fact

Proving properties of systems can be hard

Level of System (Implementation) Description



- Abstract level
  - Finitely many states (bounded size datatypes)
  - Simplification, unfaithful modeling inevitable
  - Automated proofs are (in principle) possible
- Concrete level
  - Unbounded size datatypes
    (pointer chains, dynamic containers, streams)
  - Complex datatypes and control structures
  - Realistic programming model (e.g., Java)
  - Automated proofs hard or impossible!

Expressiveness of Specification

- Simple
  - Simple or general properties
  - Finitely many case distinctions
  - Approximation, low precision
  - Automated proofs are (in principle) possible
- Complex
  - Full behavioural specification
  - Quantification over infinite or large domains
  - High precision, tight modeling
  - Automated proofs hard or impossible!

Main Approaches

Abstract programs, Simple properties	Abstract programs, Complex properties
Concrete programs, Simple properties	Concrete programs, Complex properties

Main Approaches

Model Checking, 1st part of course

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Model Checking, 1st part of course

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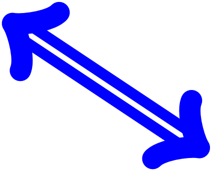
Concrete programs, Simple properties	Concrete programs Complex proper

Deductive Verification, 2nd part of course

Proof Automation

- “Automated” Proof
  (“batch-mode”)
  - Not required: interaction
  - Required: tuning of tool parameters
  - Formal specification still “by hand”

- “Semi-Automated” Proof
  (“interactive”)
  - Interaction (or lemmas) may be required
  - Need certain knowledge of tool internals
    Intermediate inspection can help
  - User steps are checked by tool



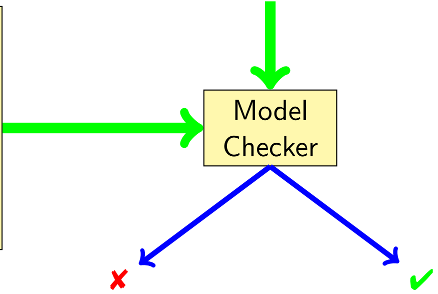
Model Checking with Spin

System Model

System Property

`[] ! (PinCritSect && QinCritSect)`

```
byte n = 0;
active proctype P() {
  ...
}
active proctype Q() {
  ...
}
```



PinCritSect = 0 1 1
QinCritSect = 1 0 1

Model Checking in Industry—Examples

- Hardware verification
  - Good match between limitations of methods and application
  - Intel, Motorola, AMD, . . .
- Software verification
  - Specialized software: control systems, protocols
  - Typically no direct checking of executable system, but of abstractions
  - Bell Labs, Microsoft

A Major Case Study with SPIN

Checking feature interaction for telephone call processing software

- Software for PathStar© server from Lucent Technologies
- Automated abstraction of unchanged C code into PROMELA
- Web interface, with SPIN as back-end, to:
  - determine properties (ca. 20 temporal formulas)
  - invoke verification runs
  - report error traces
- Finds error trace, reported as C execution trace
- Work farmed out to 16 computers, daily, overnight runs
- 18 months, 300 versions of system model, 75 bugs found
- Strength: detection of undesired feature interactions (difficult with traditional testing)
- Main challenge: defining meaningful properties

Deductive Verification with KeY

Java Code

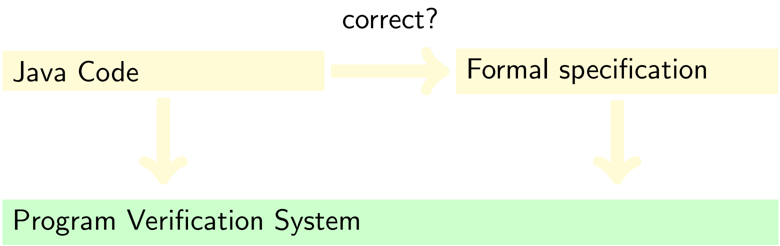
Formal specification

Deductive Verification with KeY

correct?

Java Code → Formal specification

Deductive Verification with KeY



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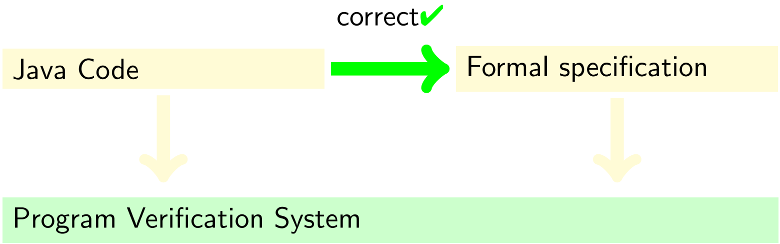

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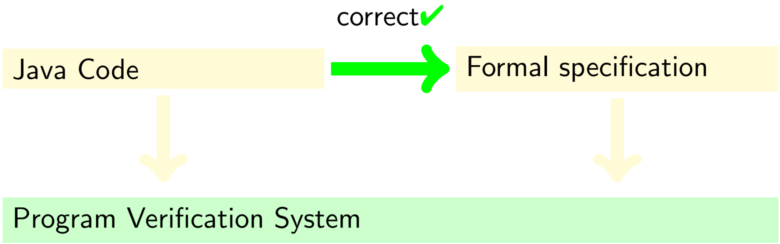

Proof rules establish relation “implementation conforms to specs”

Deductive Verification in Industry—Examples

- Hardware verification
  - For complex subsystems, mostly floating-point units
  - Intel, Motorola, AMD, ...
- Software verification
  - Safety critical systems:
    - Paris driver-less metro (Meteor)
    - Emergency closing system in North Sea
  - Libraries
  - Implementations of Protocols
  - (critical parts of) Norwegian Election Software

Major Case Studies with KeY

Java Card 2.2.1 API Reference Implementation

- Reference implementation and full functional specification
- All Java Card 2.2.1 API classes and methods
  - 60 classes; ca. 5,000 LoC (250kB) source code
  - specification ca. 10,000 LoC
- Conformant to implementation on actual smart cards
- All methods fully verified against their spec
  - 293 proofs; 5–85,000 nodes
- Total effort several person months
- Most proofs fully automatic
- Main challenge: getting specs right

Major Case Studies with KeY: TimSort

TimSort

Hybrid sorting algorithm (insertion sort + merge sort) optimized for partially sorted arrays (typical for real-world data).

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TimSort is used in

- Java (standard libraries OpenJDK, Oracle)
- Python (standard library)
- Android (standard library)
- ... and many more languages / frameworks!

TimSort: People

- Tim Peters

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- Python Guru

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- Stijn de Gouw

TimSort: People

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- Sorting Algorithm Designer
- Python Guru

- Stijn de Gouw
- Assistant Professor

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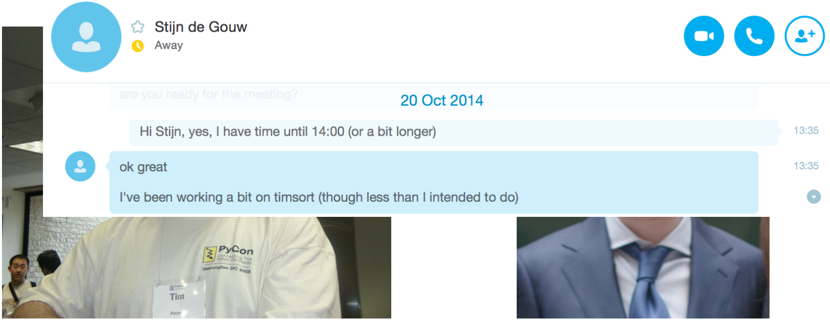

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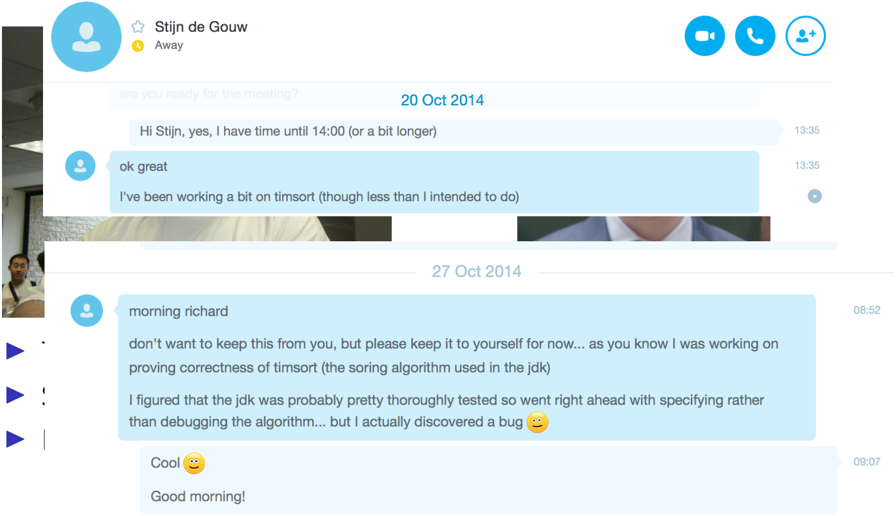

professional reasons

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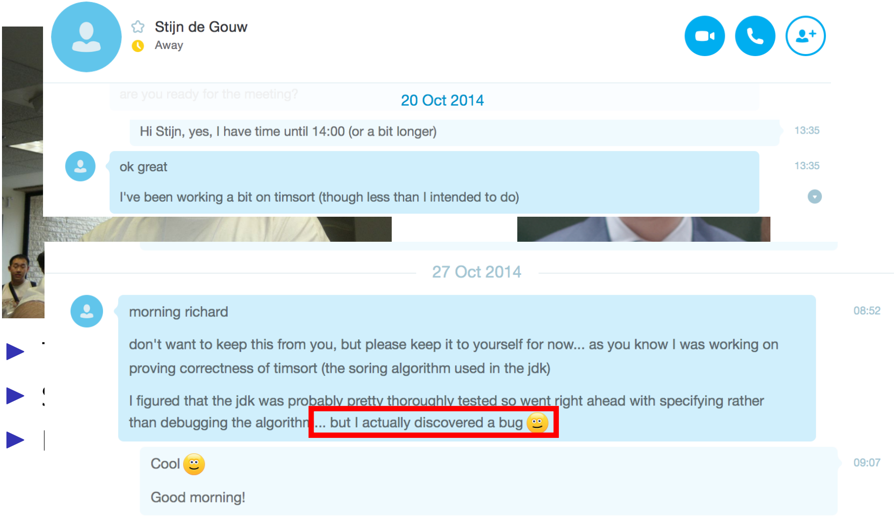

professional reasons

Major Case Studies with KeY

Found Bug in Java Libraries' main Sorting Method using KeY

- `java.util.Collections.sort` and `java.util.Arrays.sort` implement TimSort
- KeY verification of OpenJDK implementation revealed *bug*.
- Same bug present in Android SDK, Phyton library, Haskell library, ...

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Verified Fix using KeY

- Fixing the implementation
- Verified absence of the bug in new version with KeY

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Verified ...

- Fixing ...
- Verified ... bug in new version with KeY

Some researchers found an error in the logic of merge_collapse, explained here, and with corrected code shown in

...

It should be fixed anyway, and their suggested fix looks good to me.

Tim Peters via Python-Bugtracker

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It should be fixed...
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Tim Peters via ...

Congratulations to Stijn de Gouw et al.
for finding and fixing a bug in TimSort
using formal methods!
Joshua Bloch via Twitter

Tool Support is Essential

Reasons for Using Tools

- Automate repetitive tasks
- Avoid typos, etc.
- Cope with large/complex programs
- Make verification certifiable

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SPIN **web interface** developed for this course!

JSPIN front-end for SPIN

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Install first SPIN and JSPIN on your computer,
or make sure our SPIN web interface works for you.

You will gain experience in ...

- Modelling, and modelling languages

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- ...

Learning Outcomes—Knowledge and Understanding

- Explain the potential and limitations of using logic based verification methods for assessing and improving software correctness
- Identify what can and what cannot be expressed by certain specification/modeling formalisms
- Identify what can and cannot be analyzed with certain logics and proof methods

Learning Outcomes—Skills and Abilities

- Express safety and liveness properties of (concurrent) programs in a formal way
- Describe the basics of verifying safety and liveness properties via model checking
- Successfully employ tools which prove or disprove temporal properties
- Write formal specifications of object-oriented system units, using the concepts of method contracts and class invariants
- Describe how the connection between programs and formal specifications can be represented in a program logic
- Verify functional properties of simple Java programs with a verification tool

Learning Outcomes—Judgment and Approach

- Judge and communicate the significance of correctness for software development
- Employ abstraction, modelling, and rigorous reasoning when approaching the development of correctly functioning software

Literature for this Lecture

FM in SE B. Beckert, R. Hähnle, T. Hoare, D. Smith, C. Green, S. Ranise, C. Tinelli, T. Ball, and S. K. Rajamani: *Intelligent Systems and Formal Methods in Software Engineering.* IEEE Intelligent Systems, 21(6):71–81, 2006
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